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13. ABSTRACT (Maximum 200 words) Battelle, under contract to the Air Force, has prepared a design guidance document for the proposed use of site managers, contractors, and regulators. The design guidance covers permeable barrier application to sites contaminated with dissolved chlorinated solvents in groundwater. The document does not purport to replace the scientific judgment of the on-site engineer or hydrogeologist, but provides guidance on the issues and options that need to be considered based on the current understanding of the technology. The guidance addresses design, emplacement, and monitoring of permeable barriers in various hydrogeologic settings. The Remediation Technologies Development Forum's Permeable Barriers Work Group and the Interstate Technology and Regulatory Cooperation Group provided advisory support during the preparation of this document.					
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FOREWORD

The U.S. Army Corps of Engineers is dedicated to identifying and using the best technologies possible for environmental restoration. We participated in the development of this document with the Air Force to provide a practical guide for the design, construction, and monitoring of permeable barrier systems. Permeable barriers are passive in situ systems that enhance degradation of ground-water contaminants. This document guides site managers, contractors, and regulators through the steps of technology selection, data gathering, design, construction, and monitoring. Users of this guide should continue to monitor permeable barrier research and development, since this technology is still evolving.

FOR THE COMMANDER:

A handwritten signature in black ink that reads "Patricia A. Rivers". The signature is written in a cursive, flowing style.

PATRICIA A. RIVERS, P.E.
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EXECUTIVE SUMMARY

One of the most common environmental problems facing Air Force installations is the presence of chlorinated solvent-contaminated soil and groundwater. Chlorinated solvents, such as trichloroethylene (TCE) and perchloroethylene (PCE), were commonly used in aircraft maintenance, dry cleaning, and other operations and have entered the ground through leaks, spills, or past disposal practices. There may be 600 or more such sites at Air Force bases across the country. The U.S. Environmental Protection Agency (EPA) (1996) estimates that there are 5,000 Department of Defense (DoD), Department of Energy (DOE), and Superfund sites contaminated with chlorinated solvents. The Armstrong Laboratory Environics Directorate (AL/EQ) and the U.S. EPA National Exposure Research Laboratory (NERL) are conducting a cooperative research effort to design and evaluate the installation and performance of a permeable barrier groundwater interception and treatment technology. As part of this cooperative research effort, the objective of this task is to develop a permeable barrier design guidance document that would guide site managers, contractors, and regulators in the application of this technology for remediation of dissolved chlorinated solvents in groundwater.

This design guidance was prepared by Battelle under contract to the Air Force. Unlike conventional ex situ technologies, such as pump-and-treat systems, in situ technologies are more dependent on site-specific parameters. Therefore, this document does not purport to replace the scientific judgment of the site hydrogeologist or site engineer. Instead, this document points out the important considerations and various available options applicable to permeable barriers that should be taken into account during design, implementation, and monitoring.

Assisting in the development of this design guidance was the Remediation Technologies Development Forum (RTDF) Permeable Barriers Working Group (PBWG), a voluntary group of government, industry, and academic participants who share the common goal of developing more effective, less costly permeable barrier technologies. AL/EQ and NERL are members of this working group. Also providing assistance and review in the protocol preparation effort was the Interstate Technology and Regulatory Cooperation (ITRC) Permeable Barriers Subgroup, a committee consisting of representatives from the environmental protection agencies of several states in the United States.

In its simplest form, a permeable barrier consists of a trench in the path of the dissolved chlorinated solvent plume. This trench is filled with a reactive medium, such as granular iron. As the groundwater flows through this continuous reactive barrier, the chlorinated organics come in contact with the reactive medium and are degraded. The main advantage of this system is that no pumping or above-ground treatment is required; the barrier acts passively after installation.

A common permeable barrier configuration is the funnel-and-gate system. Wider plumes or heterogeneously distributed contamination can be captured with this system. Impermeable funnel walls or wings on either side of the treatment trench direct the plume toward the permeable reactive cell or gate. At some sites, this configuration can provide better control over reactive zone emplacement and plume capture.

The first decision facing site managers is whether or not the site is suitable for a permeable barrier application. The suitability of a site is affected by the following factors:

- Contaminant type
- Plume size and distribution
- Depth of aquitard

- Geotechnical considerations
- Competency of aquitard
- Groundwater velocity.

If the site is considered suitable, the next issue is whether or not the available site characterization data are sufficient to locate and design the barrier. If the site information is incomplete, additional site characterization may be required. The important site information required includes the following:

- **Aquifer Characteristics:** The aquifer characteristics that should be known include groundwater depth, depth to aquitard, groundwater velocity, site stratigraphy/heterogeneities, hydraulic conductivities of the different layers, and dimensions and distribution of the plume. This information is required to assist in hydrogeologic modeling that will be done to locate and design the permeable barrier.
- **Organic Composition of the Groundwater:** The types of chlorinated solvent contamination and the concentrations should be known. This information will be used to select appropriate reactive media, conduct treatability tests, and design the thickness of the wall.
- **Inorganic Composition of the Groundwater:** This information is required to evaluate the long-term performance of the permeable barrier and select an appropriate reactive medium. Knowledge of the presence and concentrations of calcium, magnesium, alkaline compounds (e.g., bicarbonate), nitrate, and sulfate aids in evaluating the potential for precipitate formation that may affect the reactivity and hydraulic performance of the reactive cell. Field parameters such as pH, redox potential, and dissolved oxygen are also good indicators of water quality that may affect performance.

Once the required site characterization data have been obtained, the next step is to identify and screen candidate reactive media. The main considerations in identifying initial candidates are:

- Reactivity
- Hydraulic performance
- Stability
- Environmentally compatible byproducts
- Availability and price.

Following identification of candidate reactive media, batch tests can be performed to quickly screen several candidates. If only one or two candidates have been identified, screening by batch testing may be foregone in favor of column tests. Column tests are conducted to select the final reactive medium and determine half-lives and residence times. Half-lives calculated through column tests may require adjustments for field groundwater temperatures and the potentially lower field bulk density of the reactive medium. The flowthrough thickness of the reactive cell is determined by residence time requirements and the local groundwater velocity through the reactive cell.

While treatability tests are being conducted, hydrogeologic modeling and geochemical evaluation of the site can begin. Hydrogeologic modeling can be used to define several aspects of the design. Widely available and validated models such as MODFLOW and MODPATH are generally sufficient to

achieve permeable barrier design objectives. Hydrogeologic modeling, along with site characterization data, is used to accomplish the following:

- Determine a suitable location for the permeable barrier with respect to the plume distribution, site hydrogeology, and other site features (e.g., property boundaries, underground utilities, etc.)
- Determine a suitable permeable barrier configuration (e.g., continuous reactive barrier or funnel-and-gate system)
- Determine width of the reactive cell, and for a funnel-and-gate configuration, the width of the funnel
- Estimate hydraulic capture zone of the permeable barrier
- Identify a balance between hydraulic capture zone and flowthrough thickness of the reactive cell (gate), which are two interdependent parameters
- Help in media selection and long-term performance evaluation by specifying required particle size (and hydraulic conductivity) of the reactive medium with respect to the hydraulic conductivity of the aquifer
- Develop scenarios to evaluate future potential for flow bypass due to reduced porosity resulting from precipitate formation
- Assist in planning appropriate monitoring well locations and monitoring frequencies.

Geochemical evaluation of the site can also commence while treatability tests are in progress, although knowledge of the inorganic composition of the influent and effluent is helpful to the evaluation. Geochemical evaluation may consist simply of a qualitative assessment of the potential for precipitate formation in the reactive cell based on site characterization and treatability data. Computerized geochemical codes may or may not be used, depending on site objectives.

Once the location and dimensions of the permeable barrier have been designed, the best way to emplace the barrier in the ground needs to be determined. The aquitard depth is the primary parameter that governs the emplacement method selected. Geotechnical considerations, such as presence of rocks in the subsurface, may also affect the viability of the technique (for example, by affecting the drivability of sheet piles).

Once the emplacement of the barrier is complete, the wall will have to be monitored for compliance with regulatory requirements as long as the plume is present. Additional performance monitoring may be conducted at the site manager's discretion to evaluate how closely the barrier is performing to design specifications, as well as to look for signs of any potential loss in reactive and hydraulic performance over the long term. Performance monitoring could be conducted to satisfy any of the following objectives:

- Evaluate adequate capture and treatment of the plume and ensure acceptable downgradient water quality

- Evaluate how well the barrier meets design objectives
- Evaluate the longevity of the barrier.

A cost-benefit approach should be used to evaluate the economics of a permeable barrier application. Capital costs of a permeable barrier include the following:

- Costs of the reactive medium
- Costs of the emplacement
- Technology licensing costs
- Disposal and restoration costs.

The operating and maintenance (O&M) costs of the technology include the following:

- Compliance monitoring costs
- Additional performance monitoring costs. These may vary considerably from site to site depending on the objectives
- Periodic maintenance costs. The reactive cell wall may have to be flushed or the reactive medium replaced periodically if precipitates build up to the point that reactivity or hydraulic performance is affected. Based on experience at existing sites, the incorporation of proper safety factors in the design may make it possible to keep the frequency of such maintenance as low as once in several years, if at all.

Economic benefits may accrue from being able to put the property to more productive use. Important intangible benefits, such as the risk reduction achieved, should also be considered.